Ice in the Environment: Proceedings of the 16th IAHR International Symposium on Ice
Dunedin, New Zealand, 2nd–6th December 2002
International Association of Hydraulic Engineering and Research

TWENTIETH CENTURY TRENDS IN THE ICE COVER OF THE LAURENTIAN GREAT LAKES OF NORTH AMERICA

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ABSTRACT

Trends in the annual maximum ice cover (i.e. the greatest fraction of the total surface area that is ice covered each winter) of the combined area of the five Laurentian Great Lakes of North America are analyzed over the 20th century. The extreme winters of anomalously low and anomalously high annual maximum ice cover extent over the past four decades are identified. An air temperature regression model of ice cover is used to reconstruct annual maximum ice cover over the first six decades of the 20th century. Cumulative normalized and 5-year running averages of the annual maximum ice cover illustrate variations and trends in the ice cover regime over the 20th Century. Trends and variations are discussed within the context of a recent sequence of five consecutive mild winters.

INTRODUCTION

The Laurentian Great Lakes of North America (Fig. 1) have a combined surface area of about 244,000 km^2, a combined volume of approximately 22,800 km^3, and contain 95 % of the USA's surface water supply. Thus they are extremely important to the economies of the United States (U.S.) and Canada. The potential impact of climate change on the lakes ecosystem and regional economy is of concern to both nations (Mortsch et al., 1997; Lofgren et al., in press). Lake ice is a sensitive index of regional winter climate, (Assel and Herche, 1998; Assel and Robertson, 1995). Magnuson et al., (2000) have shown that over the past 150 years there is a trend for later freeze-up dates and

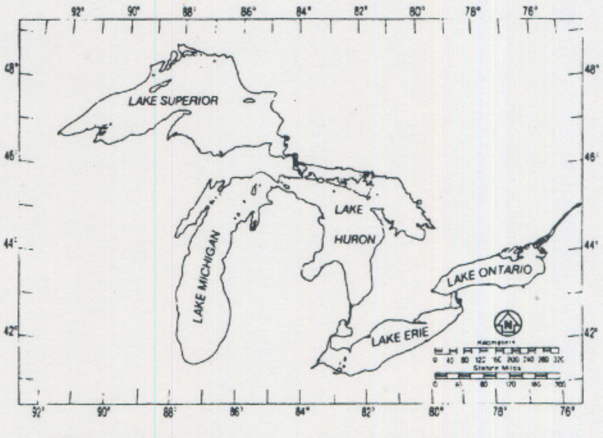

Figure 1: Laurentian Great Lakes of North America.

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earlier break-up dates at lake and river sites over the Northern Hemisphere (including Grand Traverse Bay in Lake Michigan). Assel et al. (in press) expanded upon the Great Lakes analysis by using a different ice metric, the Annual Maximum Ice Cover (AMIC) for each Great Lake. They found that the winter AMIC averaged over the winters 1998, 1999, 2000, and 2001 was the lowest on record on four of the five Great Lakes and thus may be the harbinger of a lower Great Lakes ice regime. Here we modify and update that study by examining the AMIC of the combined area of the five Great Lakes and by including an analysis of the AMIC for winter 2002. The average AMIC of the past five winters is placed in a historical perspective by comparing it with running averages of AMIC over the past century. This analysis is based on observed AMIC data for the winters 1963–2002 and reconstructed AMIC data for the previous six decades of the 20th Century. We also briefly review recent studies (Rodionov et al., 2001; Assel and Rodionov, 1998) that examine atmospheric circulation patterns associated with the extreme AMICs over the past four decades.

OBSERVED ANNUAL MAXIMUM ICE COVER 1963–2002

Systematic observations of Great Lakes ice cover over the past four decades were used to calculate AMIC; data sources and methods are given in Assel et al. (in press). Here we calculated the average AMIC of the five Great Lakes as the area-weighted sum of the AMIC of each Great Lake divided by the total area of the five Great Lakes. Winter 2002 ice cover data were obtained from the National Ice Center over the Internet at: http://www.natice.noaa.gov/greatlakes.htm.

Temporal patterns (1963 – 2002)

The AMIC over the past 40 winters averaged 57.7 %, it was at a maximum of 97.4 % in 1979, and it was at a minimum of 14.8 % in 2002 (Fig. 2). There is no significant linear trend in the AMICs over the entire 40 winters. However, there is a linear trend (seen clearly in the 5-year moving average) for decreasing AMIC between the late 1970s and 2002. This is due to an abrupt shift to higher ice cover regime in the late 1970s (Assel and Rodionov, 1998) and a general decline in AMIC in the 1980s and 1990s, Assel et al. (2000), with some notable exceptions (Assel et al., 1996). A majority of the lowest quartile of the AMICs on individual Great Lakes occurred during the winters from 1983 to 2001 (Assel et al., in press). Our results are in agreement with that study in that six winters between 1983 and 2002 (1983, 1987, 1995, 1998, 1999, 2002) had AMICs of less than 36.8 %, that is greater than one standard deviation (Std = 20.9 %) below the 40-winter mean. Winter 2002 established a new record low AMIC, and the 5-year (1998–2002) running average AMICs is the lowest on record (Fig. 2).

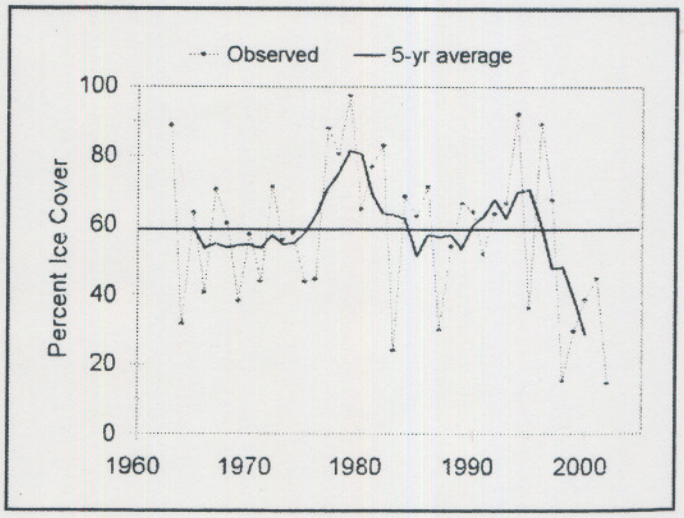

Figure 2: Annual Maximum Ice Cover 1963 – 2002.

Extreme AMICs and associated atmospheric circulation patterns

The AMICs for winters 1994 and 1998 were very close to the record extreme winters of 1979 and 2002, respectively. In 1998 the lakes were ice free with the exception of ice extending lakeward of the shallow shoal areas, bays, and shore region in general. During that winter a strong west to east circulation pattern in the upper atmosphere brought mild air of Pacific Ocean origin across the continent toward the Great Lakes most of the winter and greatly reduced the frequency of polar air masses in the region (Assel et al., 2000). In 1994 in contrast over 90 % of the surface of the Great Lakes was ice covered. In that winter an anomalously strong clockwise atmospheric circulation over the central North Pacific Ocean in combination with a strong extension of the polar vortex south from Hudson Bay produced a more meridional (north to south) circulation that directed frequent Arctic and polar air masses toward the Great Lakes (Assel et al., 1996). In general Assel and Rodionov (1998) and Rodionov et al. (2001) found that AMIC is above average when the upper air pattern is characterized by an intensification of the ridge over the west cost of North America in conjunction with a deeper than average trough over the southeastern U.S. (Fig. 3). An Aleutian Low displaced east of its normal location and an intensification of the Hudson Bay Low contributes to intensified meridional flow associated with this pattern. Below average AMIC (increased zonal flow) is enhanced when the opposite anomalies in the upper air circulation pattern occur, that is a weakening of the west coast ridge and trough over the southeast U.S.

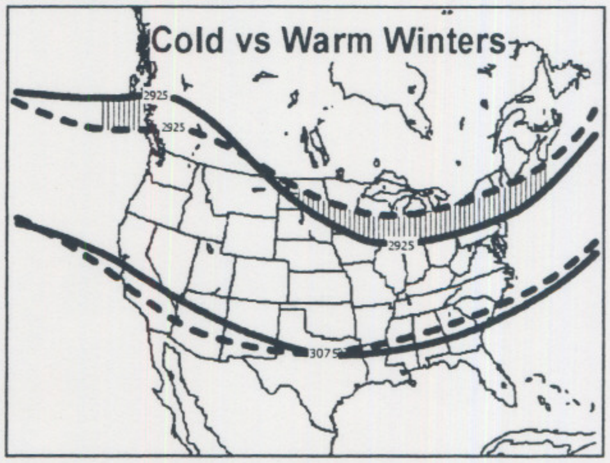

Figure 3: The 700 hPa ridge (2925 m contour) over west coast and trough (3075 m contour) over southeastern United States for cold (solid line) and mild (dashed line) winters, from Rodionov and Assel (2001).

ANNUAL MAXIMUM ICE COVER DURING THE TWENTIETH CENTURY

Air temperatures were used to model AMIC (Fig. 4) in order to extend the analysis of the trends in AMIC back to the start of the 20th century. A winter severity index (WSI) composed of the monthly averaged air temperatures for November through February at Duluth, Minnesota, Sault Ste. Marie, Michigan, Detroit, Michigan, and Buffalo, New York was found to have a high and significant correlation with AMIC (Assel et al., 1996). The model, recalibrated to

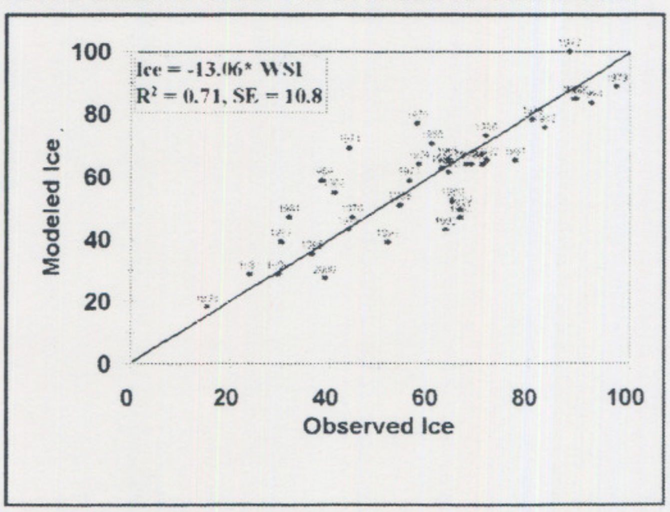

Figure 4: Modeled vs. observed AMIC.

include the winters of 1996 through 2000, was used to reconstruct ice cover for the first six decades of the 20th Century.

Normalized AMIC trends

The long-term mean (LTM) AMIC is 57.1 %, its Std is 19.8 %. The normalized values ([AMIC – LTM] / Std) of the AMIC each winter, sometimes called the z-score, are shown in Fig. 5. Values prior to 1962 are from the WSI model. The lowest AMIC occurred in 1932 and the highest in 1904; the modeled AMIC for those years are 0 %

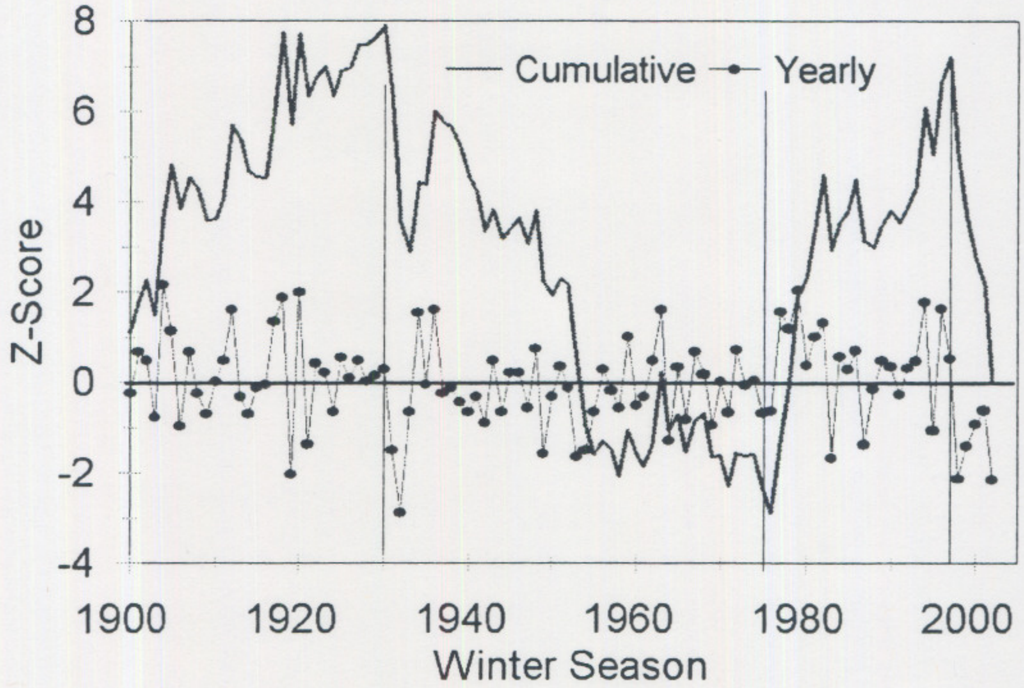

Figure 5: Yearly and cumulative normalized AMIC. The horizontal line is the LTM. The vertical lines are the approximate boundaries between different trends.

and 100 % respectively. No significant linear trend was found spanning the entire 105-year record, but the cumulative z-score, the running sum of the z-scores from the beginning of record to any given year, reveals that there was a trend for AMICs to be larger than the mean from 1898 to about 1930. This trend was reversed between 1930 and the mid 1970s, when the general trend was for AMICs to be below the LTM. The third and fourth trends for increases (late 1970s to mid-to-late 1990s) and decreases (late 1990s to early 2000s) from the LTM, respectively, are due in part to the pattern described earlier, that is to the abrupt increase in AMICs in the late 1970s and early 1980s and the larger decline in AMICs during the last five winters of the record. Regression analysis of AMIC vs. year revealed a weak linear decline in AMIC of 0.160 % per year from 1898 to 1976 and a much stronger decline of 1.69 % per year from 1977 to 2002 (both significant at $\alpha = 90$ %).

Five-Year average AMIC trends and extremes.

The AMIC averaged over a five-winter period provides another aspect of the climatology of the AMIC over the 20th Century. The four ice cover periods noted above with respect to the LTM are evident in the plot of the 5-year running means (Fig. 6). The highest and lowest 5-year mean AMIC occurred after the mid 1970s. The three highest 5-year running mean AMICs (1977–81, 81.5 %), (1978–82, 80.6 %), and (1976–80, 75.0 %) started in the mid-to late 1970s. Two of the three lowest 5-year mean AMICs started after the mid 1990s, the most recent being the lowest, (1998–2002, 28.9 %), (1929–33, 38.9 %), and (1997–01, 39.3 %).

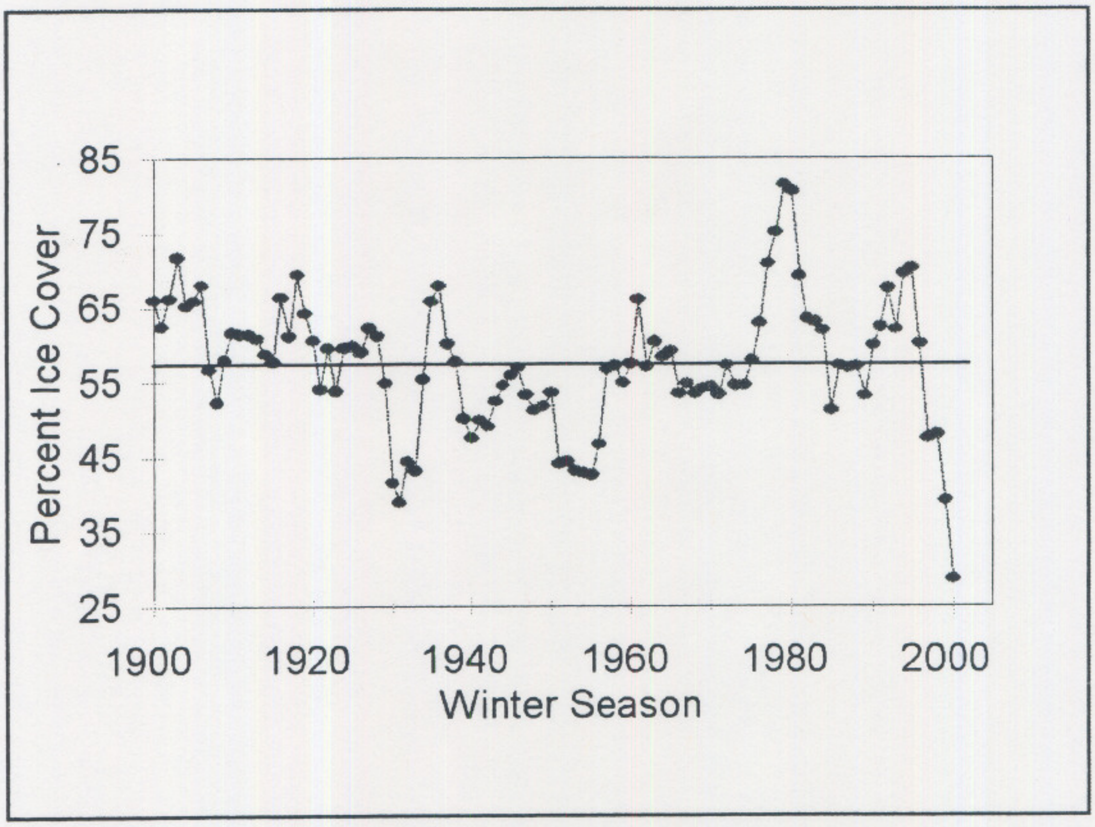

Figure 6: Five-year running averages of AMIC plotted on 3rd year.

Ice cover regimes and distribution of the extreme AMICs during the 20th Century.

A Wilcoxon rank sum test (Ferguson, 1976) shows that with the exception of means for 1898–1930 (61.8 %) and 1977–1997 (66.6 %), the mean AMICs for the other periods noted above were significantly different ($p = 5$ % level) (Table 1), providing evidence for different ice cover regimes during the 20th Century. The decadal distribution of the top 20 % (21 highest and 21 lowest AMIC winters), of the extreme winters shows that most of the severe winters occurred during the two high ice regimes but, except for the decade of the 1970s, the frequency of the lowest 20 % of the AMICs was distributed about the same over both high and low AMIC regimes during the 20th Century, including the first years of the first decade of the 21st Century. The reason for this is not known. It may be associated with the general global warming that has progressed during the 20th Century and continues into the first years of the first decade of the 21st Century.

Table 1: Means Test for Differences				
	1898 1930	1931 1976	1977 1997	1998 2002
1898 1930	61.8			
1931 1976	different	52.4		
1977 1997	same	different	66.6	
1998 2002	different	different	different	28.6

SUMMARY AND CONCLUSIONS

In this paper we examined a 40-year observed data set and a 65-year reconstructed data set of AMIC to identify trends and regimes of Great Lakes ice cover over the 20th Century. We found four periods when the trend in AMICs were generally above or below the LTM: 1) above: 1898–1930, 2) below: 1931–1976, 3) above:1977–1997, and 4) below: 1998–2002. The mean AMIC for 1898–1930 was statistically not different than that for 1977–1997. A majority of the 21 greatest AMICs for individual winters occurred during these two high ice cover regimes, while the 21 lowest AMICs were more evenly distributed over the four AMIC regimes. The means for the other regimes were significantly different from each other and from the two high ice cover regimes. We found a weak linear trend (0.16 % per year) for decreasing AMIC between 1898 and 1976, and a much stronger linear trend for decreasing AMIC from 1977 to 2002 (1.69 % per year). So even though there were significant periods when the AMIC was increasing, the general trend over the 20th Century was for decreasing AMICs. The AMICs from 1995 through 2002 are remarkable in that five of these eight winters are ranked among the top 20 % of the mildest winters over the past 105 years, and the average AMIC of the most recent five winters is the lowest 5-year average over the period of record. Have we entered into a new low ice cover regime milder than any that has occurred over the past 100 years? It is still too early to say for sure. The 5-year average AMICs in the 1930s and 1950s (Fig. 6) provide evidence that it is possible to have dramatic reversals in trend (lower to higher) on decadal time scales. In addition, the most recent 10-year moving average (1993 – 2002) is only the 8th lowest over the past 105 years. Given that fact, it would be more prudent to wait another 5–10 years prior to claiming we have entered into a new and yet lower ice cover regime. However, it is also prudent to start thinking about how a lower ice cover regime might affect the ecology of the Great Lakes and the regional economy.

ACKNOWLEDGMENT

This is GLERL contribution number 1249.

REFERENCES

Assel, R.A., Cronk, K. and Norton, D.C. Recent trends in Great Lakes ice cover. *Climate Change* (in press).

Assel, R.A., Janowiak, J.E., Boyce, D., O'Connors, C., Quinn, F.H. and Norton, D.C. Laurentian Great Lakes ice and weather conditions for the 1998 El Nino winter. *Bul. Am. Met. Soc. 81*(4): 703–717 (2000).

Assel, R.A. and Herche, L.R. Ice-on, ice-off, and ice duration for lakes and rivers with long-term records. In *Proceedings of the 14th IAHR Symposium on Ice,* Clarkson University, Potsdam, NY, July 27–31 (1998).

Assel, R.A. and Rodionov, S. Atmospheric teleconnections for annual maximal ice cover on the Laurentian Great Lakes. *Inter. J. Climatology 18*: 425–442 (1998).

Assel, R.A., Janowiak, J., Boyce, D. and Young, S. Comparison of 1994 Great Lakes winter weather and ice conditions with previous years. *Bul. Am. Met. Soc. 77*(1): 71–88 (1996).

Assel, R.A. and Robertson, D.M. Changes in winter air temperatures near Lake Michigan during 1851–1993, as determined from regional lake-ice records. *Limno. & Ocean. 40*(1): 165–176 (1995).

Ferguson, G.A. *Statistical Analysis in Psychology & Education.* 4th Edition, McGraw-Hill, 1976) 520p.

Lofgren, B.M., Quinn, F.H., Clites, A.H., Assel, R.A., Eberhardt, A.J. and Luukkonen, C.L. Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs. *J. Great Lakes Res.* (in press).

Magnuson, J.J., Robertson, D.M., Benson, B.J., Wynne, R.H., Livingston, D.M., Arai, T., Assel, R.A., Barry, R.G., Card, V., Kuusisto, E., Granin, N.G., Prowse, T.D., Stewart, K.M. and Vuglinski, V.S. Historical trends in lake and river ice cover in the northern hemisphere. *Science 289*: 1743–1746 (2000).

Mortsch, L.D., Quon, S., Craig, L., Mills, B. and Wrenn, B. eds. Adapting to climate change and variability in the Great Lakes-St. Lawrence Basin. In *Proceedings of a Binational Symposium,* Toronto, Ontario, Canada. May 13–15 (1997).

Rodionov, S., Assel, R.A. and Herche, L.R. Tree-structured modeling of the relationship between Great Lakes ice cover and atmospheric circulation patterns. *J. Great Lakes Res. 27*(4): 486–502 (2001).

Rodionov, S. and Assel, R.A. A new look at the Pacific/North America Index. *J. Geophys. Res. Lett. 28*(8): 1519–1522 (paper number 2000GL012185) (2001).

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International Association of Hydraulic Engineering and Research

ICE IN THE ENVIRONMENT

VOLUME ONE

Edited by Vernon Squire and Pat Langhorne
University of Otago, Dunedin, New Zealand

Proceedings of 16th International Symposium on Ice
Dunedin, New Zealand, 2–6 December 2002

Available from
Department of Physics
University of Otago
PO Box 56
Dunedin
New Zealand

ISBN 1-877139-52-1
Cover pictures by John Douglas and Pat Langhorne
Cover designed by Peter Scott

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Printed at the University of Otago, New Zealand